$B_{d,s} \to \ell^+\ell^-$ in the two–Higgs–doublet model

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Why new Higgs physics?

We have no direct measurements of EWSB mechanism.

An enlarged Higgs sector is often a feature of models of New Physics.

$\rightarrow$ Interesting to search for new Higgs physics.

Higgs bosons couple to fermions proportional to fermion mass:
– 3rd generation couplings are largest.
– B sector can potentially yield signals.

New Physics from rare B decays

Look at processes that are suppressed (or nonexistant) in the SM.
$\rightarrow$ Better chance for New Physics to compete with the SM process at a detectable level.

• In general: NP which enters at the loop level can compete with SM if SM process happens only at one–loop.

• New Higgs physics: Helicity suppression $\rightarrow$ factors of lepton mass in SM amplitude.
Lepton Yukawa couplings could be relevant.

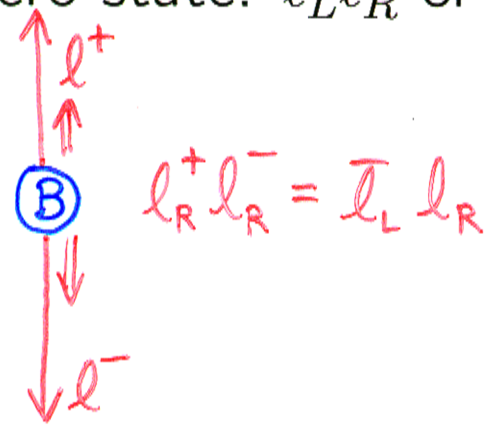
Leptonic B decays in the SM:
– $b \rightarrow (d, s)$ flavor–changing loop
– helicity suppressed
$\rightarrow$ Chance to look for new Higgs physics.

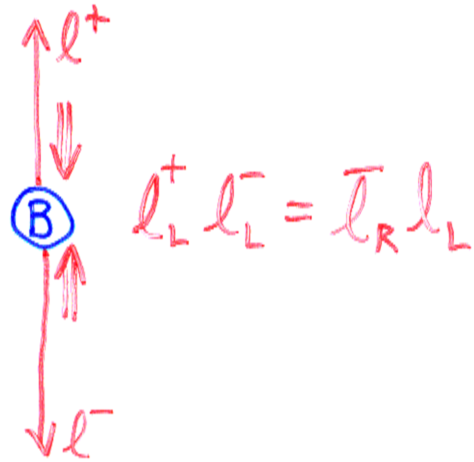
Outline

- $B \to \ell^+\ell^-$ in the Standard Model
- $B \to \ell^+\ell^-$ in the Two–Higgs–Doublet Model
- Conclusions

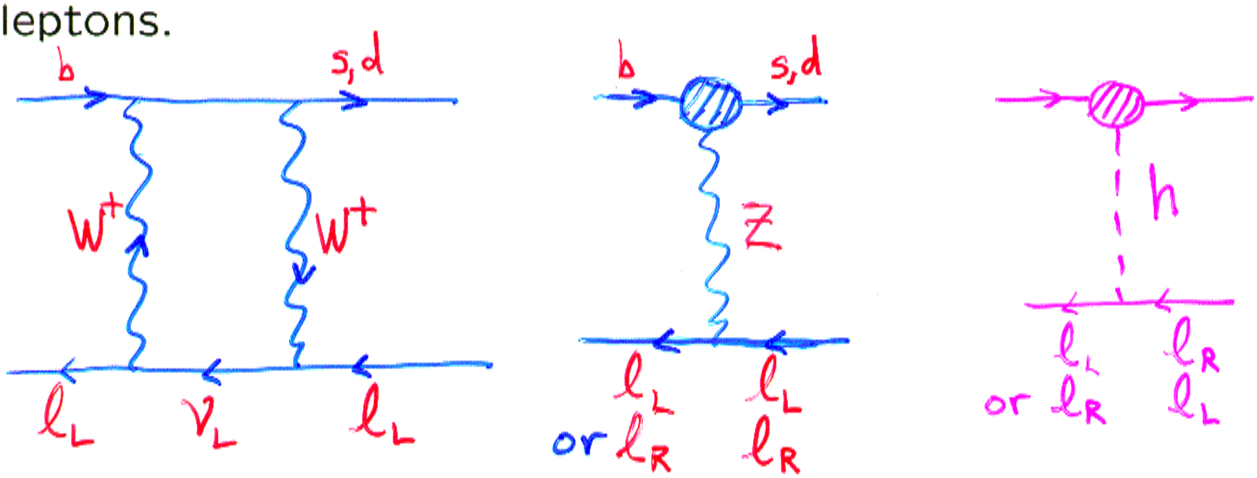
Helicity suppression in the SM

$B_{d,s}$ is spin–zero so it must decay to a spin–zero state: $\bar{\ell}_L \ell_R$ or $\bar{\ell}_R \ell_L$.





However, main SM contributions have wrong helicity structure; must flip the spin of one of the outgoing leptons.



For comparison, there is no helicity suppression in $B \to X_s \ell^+ \ell^-$, so extended Higgs contributions are negligible compared to SM.

Effective Lagrangian contributing to $B \to \ell\bar{\ell}$:

$$\mathcal{L} = H(\bar{s}\gamma_\mu Lb)(\bar{\ell}\gamma^\mu\gamma_5\ell) + P(\bar{s}Rb)(\bar{\ell}\gamma_5\ell) + S(\bar{s}Rb)(\bar{\ell}\ell)$$

Hadronic matrix elements:

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 b(x)|\bar{B}\rangle = i f_B P_B^\mu e^{-iP_B\cdot x}$$
$$\langle 0|\bar{s}\gamma_5 b(x)|\bar{B}\rangle = -i f_B m_B e^{-iP_B\cdot x}.$$

Helicity suppression: $P_B^\mu = (p_\ell + p_{\bar{\ell}})^\mu$, use Dirac equation:

$$P_B^\mu(\bar{\ell}\gamma_\mu\gamma_5\ell) = -2m_\ell(\bar{\ell}\gamma_5\ell)$$

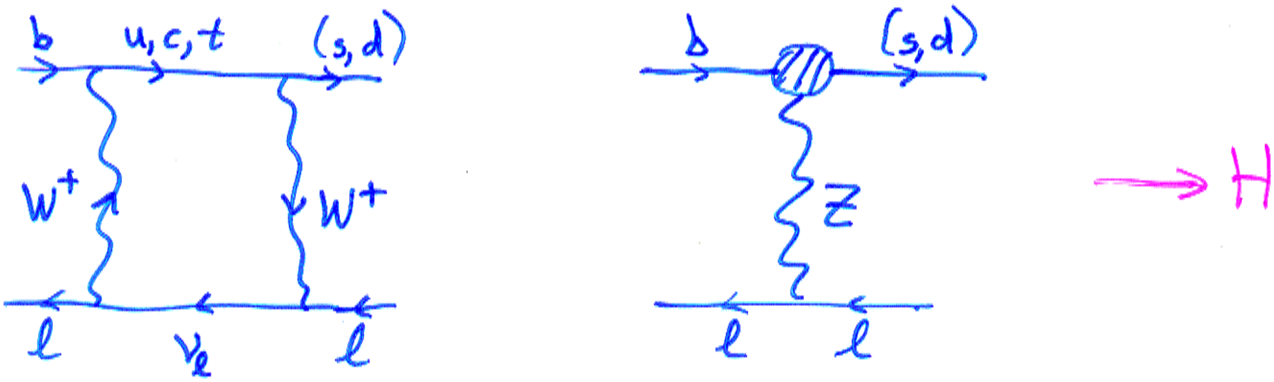
Operator coefficients contribute to the decay width as follows:

$$\Gamma = \frac{m_B^3 f_B^2 \kappa}{32\pi}\left(\left|-2\frac{m_\ell}{m_B}H + P\right|^2 + \kappa^2|S|^2\right)$$

$\kappa = \sqrt{1 - 4m_\ell^2/m_B^2}$ is a kinematic factor.

SM diagrams and formulae

Box, Z–penguin:

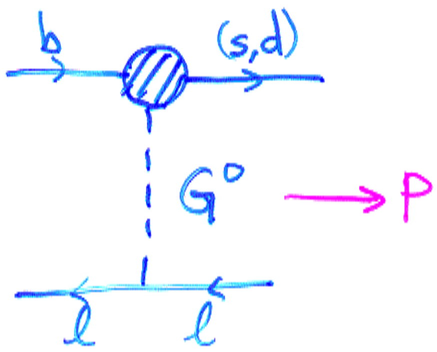


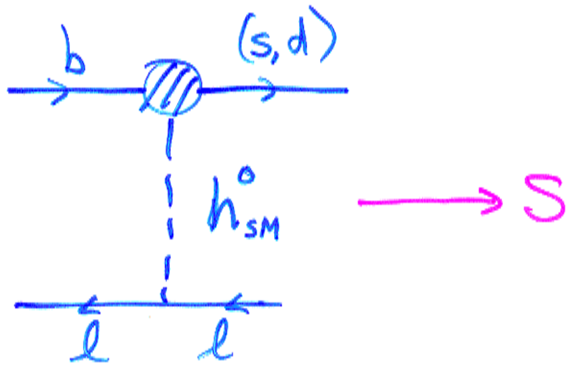
$$\longrightarrow H_{\text{SM}} = \frac{g^4}{8(16\pi^2)M_W^2} V_{ts}^* V_{tb}$$
$$\times \frac{x_t}{(x_t-1)^2}\left[-\tfrac{1}{2}(x_t-1)(x_t-4) - \tfrac{3}{2}x_t \log x_t\right]$$

$(x_t = \bar{m}_t^2/M_W^2 \simeq 4.3)$

[Inami & Lim 1981, Grządkowski & Krawczyk 1983, Krawczyk 1989, Skiba & Kalinowski 1993]

G^0, h^0 penguins:





$$P_{\mathrm{SM}} = \frac{g^4}{8(16\pi^2)M_W^2} V_{ts}^* V_{tb} \frac{m_b m_\ell}{M_Z^2} \times \frac{x_t}{(x_t-1)^2}\left(6 - 7x_t + x_t^2 + 2\log(x_t) + 3x_t\log(x_t)\right)$$

$$S_{\mathrm{SM}} = -\frac{g^4}{8(16\pi^2)M_W^2} V_{ts}^* V_{tb} \frac{m_b m_\ell}{M_{h^0}^2} \times x_t\left(\frac{3}{2} + \frac{M_{h^0}^2}{M_W^2}\frac{3 - 4x_t + x_t^2 + 4x_t\log(x_t) - 2x_t^2\log(x_t)}{4(x_t-1)^3}\right)$$

The contributions of P_{SM} and S_{SM} to Γ are suppressed by a factor of m_b^2/M_W^2 compared to the contribution of H_{SM}.
$\rightarrow$ Neglect P_{SM} and S_{SM}.

In the 2HDM, we will find contributions to P and S that go like $m_b^2 \tan^2\beta/M_W^2$ and are no longer negligible for large $\tan\beta$.

For $\tan\beta = 50$, $m_b \tan\beta \simeq 200$ GeV.

SM BRs and current limits

Current experimental limits on the branching ratios of $B_{d,s} \to \ell\bar{\ell}$:

B_d Mode	Expt. Limit	SM Pred.	x above
$e\bar{e}$	$< 5.9 \times 10^{-6}$ [CLEO]	2.6×10^{-15}	2×10^{9}
$\mu\bar{\mu}$	$< 6.8 \times 10^{-7}$ [CDF]	1.1×10^{-10}	6000
$\tau\bar{\tau}$	no upper limit	3.1×10^{-8}	–

B_s Mode	Expt. Limit	SM Pred.	x above
$e\bar{e}$	$< 5.4 \times 10^{-5}$ [L3]	7.1×10^{-14}	8×10^{8}
$\mu\bar{\mu}$	$< 2.0 \times 10^{-6}$ [CDF]	3.0×10^{-9}	700
$\tau\bar{\tau}$	no upper limit	6.5×10^{-7}	–

Tevatron has the potential to do best (closest to SM prediction) on $B_s \to \mu\bar{\mu}$.

BaBar expected 90% CL reach with 30 fb^{-1} [from BaBar Physics Book]:

B_d only Mode	Expt. Reach	SM Pred.	x above
$e\bar{e}$	$< 5.0 \times 10^{-7}$	2.6×10^{-15}	2×10^{8}
$\mu\bar{\mu}$	$< 5.0 \times 10^{-7}$	1.1×10^{-10}	5000
$\tau\bar{\tau}$	$< 2.0 \times 10^{-3}$	3.1×10^{-8}	60,000

Running on the $\Upsilon(4s)$, BaBar can only produce B_d.

Input parameters for numerical calculations

The B_d BRs are taken from the BaBar Physics Book.

The parameters used in the calculations of the B_s BRs are given below.

Parameter	Expt. value	value used	source
M_{B_s}	5.37 GeV	5.37 GeV	PDG 1998
$\Gamma_{B_s}^{\text{total}}$	$4.27 \pm 0.18 \times 10^{-13}$ GeV	4.27×10^{-13} GeV	PDG 1998
f_{B_s}	0.245 ± 0.030 GeV	0.245 GeV	Lattice '99
$m_b^{\overline{\text{MS}}}(m_b^{\overline{\text{MS}}})$	4.25 ± 0.08 GeV	4.25 GeV	Beneke, Signer, Hoang
$\|V_{ts}\|$	0.040 ± 0.002	0.040	PDG 2000
$m_t^{\overline{\text{MS}}}(m_t^{\overline{\text{MS}}})$	167 ± 5 GeV	167 GeV	

B_s versus B_d

B_s: $\mathcal{M} \sim V_{tb}V_{ts}^*$
B_d: $\mathcal{M} \sim V_{tb}V_{td}^*$

$BR \propto |V_{t(d,s)}|^2$.

Tevatron: 3× fewer B_s than B_d.
But: ratio of BRs $\sim \left(\frac{V_{td}}{V_{ts}}\right)^2 < (0.24)^2 \simeq 0.06$ [PDG 1999].
Therefore Tevatron has greater NP reach with B_s.

$B \to \ell\bar{\ell}$ in 2HDM

We consider the non–supersymmetric Type II 2HDM.

Model contains two Higgs doublets,

$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \to$ couples to d, ℓ

and $\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \to$ couples to u.

EWSB $\to$ $\begin{matrix} G^\pm, G^0 \\ H^\pm, A^0, h^0, H^0 \end{matrix}$ $\quad\quad$ $\tan\beta = \frac{v_2}{v_1}$

Down–type quark and charged lepton Yukawa couplings $\sim g \frac{m}{M_W} \tan\beta$

SM: Contribution to Γ is proportional to $g^4\left(\frac{m_\ell}{m_B}\right)$.

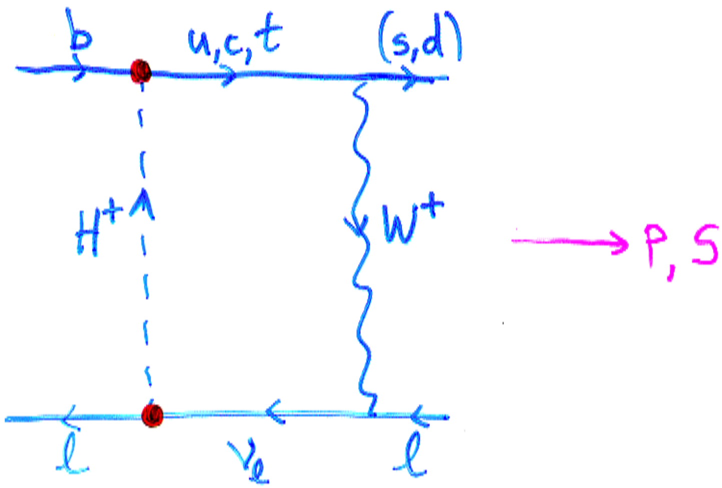
2HDM: Some of the diagrams (box, penguins) give contributions that are proportional to

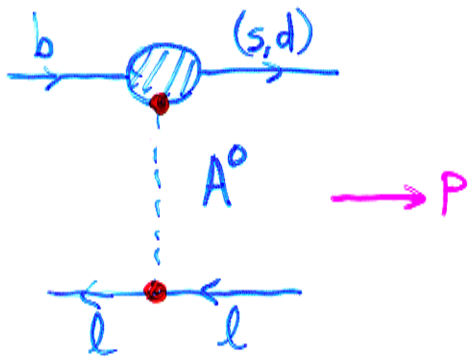
$$g^4\left(\frac{m_b m_\ell \tan^2\beta}{M_W^2}\right) \simeq g^4\left(\frac{m_\ell}{m_B}\right)\left(\frac{m_b \tan\beta}{M_W}\right)^2.$$

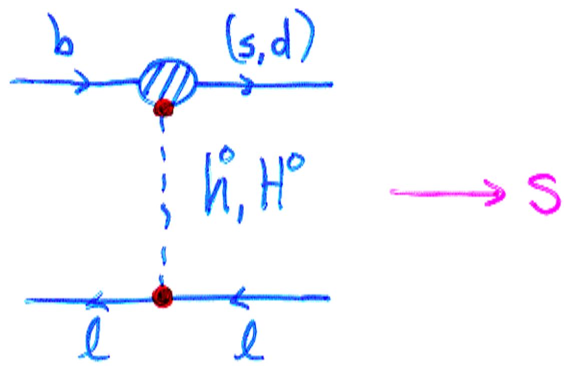
The $\tan\beta$ enhancement makes these 2HDM contributions comparable to the SM contribution.

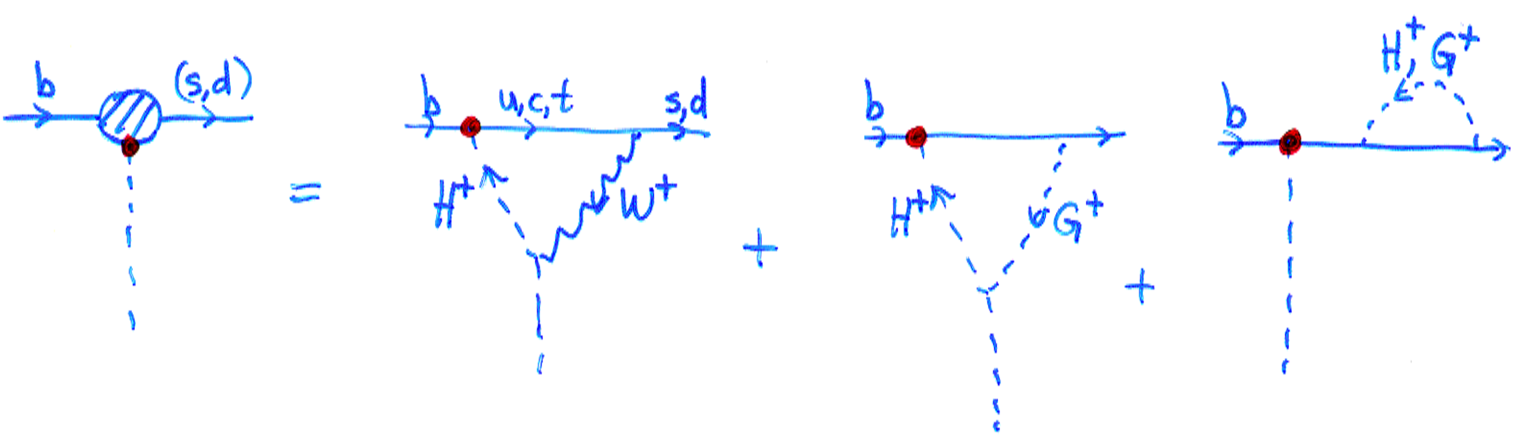
For example, for $\tan\beta = 50$, $m_b \tan\beta \sim 200$ GeV.

2HDM diagrams



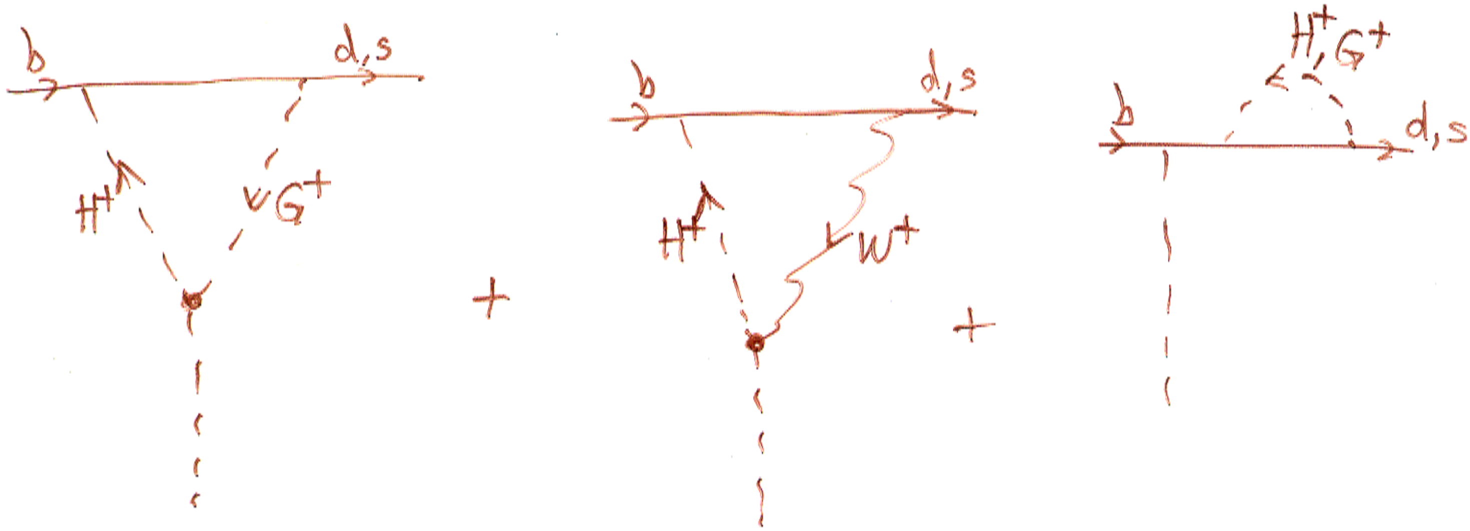






A^0, h^0, H^0 penguins: Dependence on M_{A^0,h^0,H^0} cancels.

e.g.: $G^+H^-A^0$ vertex $= -\frac{g}{2M_W}(M_{H^+}^2 - M_{A^0}^2)$.
$1/M_{A^0}^2$ from A^0 propagator.



Gauge dependence cancels between box and penguins
$\rightarrow$ Gauge dependent pieces of penguins must be independent of M_{A^0,h^0,H^0}.

To $\mathcal{O}(\tan^2\beta)$, BR depends only on M_{H^+} and $\tan\beta$.

2HDM contributions

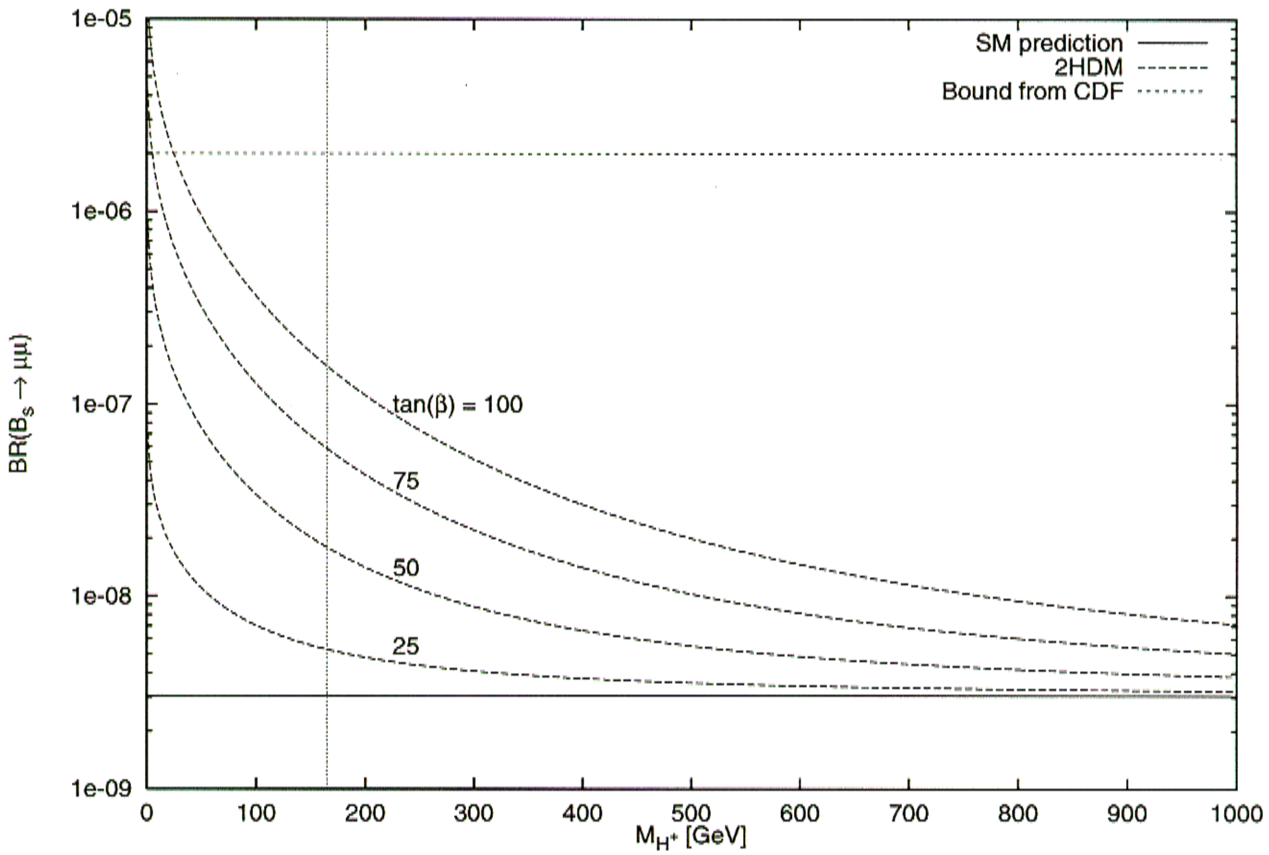
Total 2HDM contribution to $B_s \to \ell\bar{\ell}$ proportional to $\tan^2\beta$:

$$P_{\text{2HDM}} = -S_{\text{2HDM}} = \frac{g^4}{8(16\pi^2)M_W^2} V_{ts}^* V_{tb} \times \frac{m_b m_\ell \tan^2\beta}{M_W^2} \frac{1}{\left(\frac{M_{H^+}^2}{m_t^2} - 1\right)} \log\left(\frac{M_{H^+}^2}{m_t^2}\right).$$

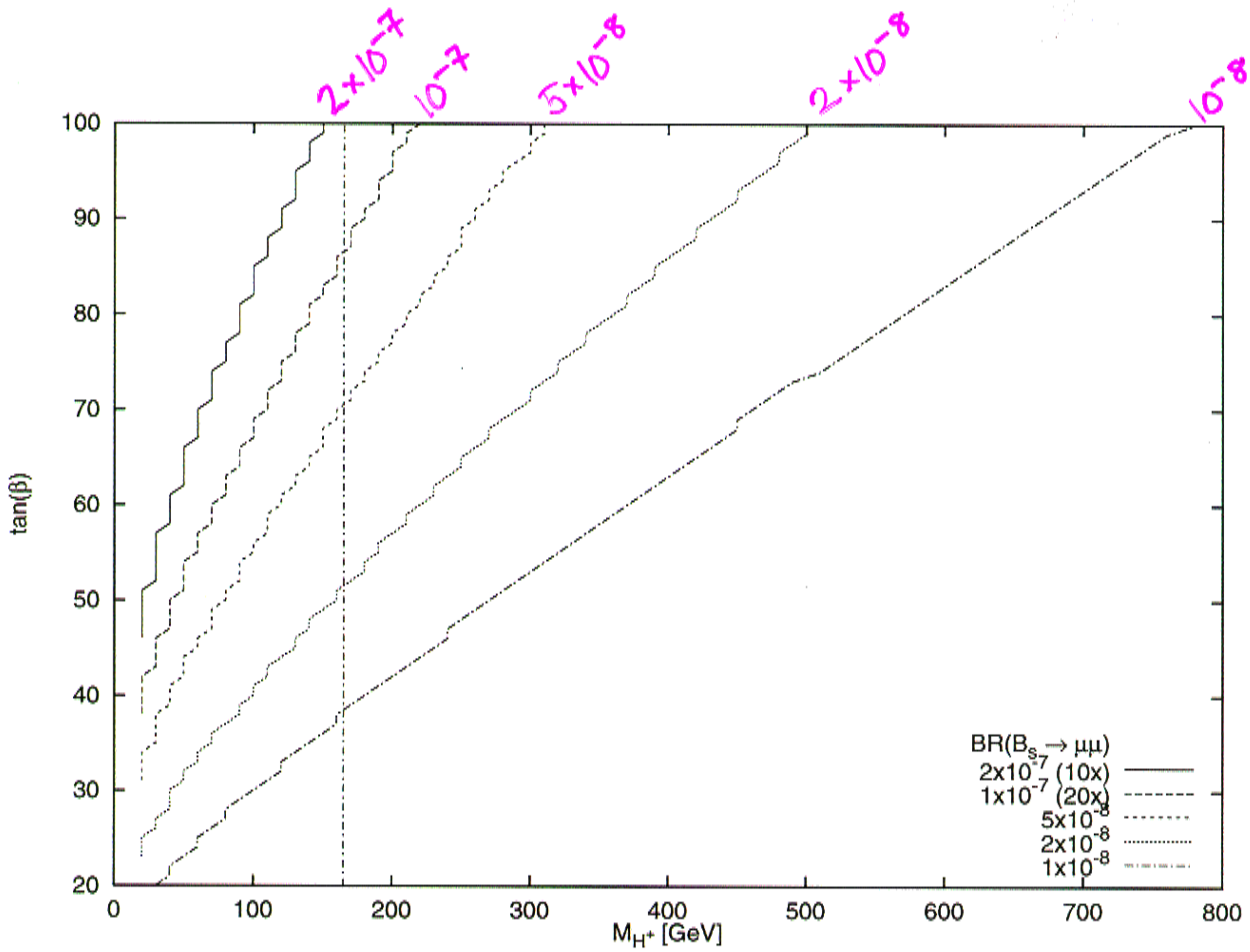
Sign(P_{2HDM}) = sign($-H_{\text{SM}}$) so there is constructive interference.

$$\Gamma = \frac{m_B^3 f_B^2}{32\pi}\kappa\left(\left|-2\frac{m_\ell}{m_B}H_{\text{SM}} + P_{\text{2HDM}}\right|^2 + \kappa^2 \left|S_{\text{2HDM}}\right|^2\right)$$

Probing the large $\tan\beta$ 2HDM



$\mathcal{B}(B_s \to \mu\bar{\mu})$ in the 2HDM as a function of M_{H+}.
($M_{H+} > 165$ GeV in Type II non–SUSY 2HDM from CLEO $b \to s\gamma$.)



SM: 3×10^{-9}

Regions of M_{H+}, $\tan\beta$ parameter space probed by measurements of $\mathcal{B}(B_s \to \mu\bar{\mu})$.

Compare DZero exclusion from direct $t \to H^+ b$ search: Can only probe $M_{H+} < m_t - m_b \simeq 170$ GeV.

Conclusions

Tevatron Run II measurement of $\mathcal{B}(B_s \to \mu\bar{\mu})$ will be the best in the world.

With sufficient luminosity, we can begin to probe the large $\tan\beta$ 2HDM.

How well can we do?